NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

NSMRL REPORT 1051

THE EFFECT OF BACKGROUND LUMINANCE ON COLOR-CODING

by

Alan R. Jacobsen

Naval Medical Research and Development Command
Research Work Unit M0100.001-1022

Released by:

W. C. Milroy, CAPT, MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

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ALAN R. JACOBSEN, Ph.D.

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NAVSUBMEDRSCHLAB

SUMMARY PAGE

PROBLEM:

To determine the effect of background raster luminance level on the ability to learn and recall color coded information presented on CRT terminals.

FINDINGS:

Performance was significantly worse on a low luminance background raster as compared to an intermediate luminance raster which appeared as a shade of middle gray.

APPLICATION:

In visual displays where there is a need to discriminate between more than six or seven colors, an intermediate luminance background raster, relative to a completely dark one, will improve color discriminability and performance on many tasks presented via visual CRT displays.

ADMINISTRATIVE INFORMATION

This information was conducted as part of the Naval Medical Research and Development Command Work Unit M0100.001-1022 - "Enhanced performance with visual sonar displays." It was submitted for review on 21 May 1985, approved for publication on 15 July 1985, and designated as NSMRL Report No. 1051.

ABSTRACT

The effect of background raster luminance on the ability to learn and recall color coded information was studied via a paired-associates paradigm. Twenty colored circles, paired with two-digit numbers were presented on a color graphics CRT terminal. On test trials each colored circle was presented by itself and observers were required to verbally recall the two-digit number that was previously paired with the target color. Time to recall as well as actual responses were both recorded. Two raster luminance levels were tested: dark or perceptual black and one that appeared to be a shade of middle gray.

Ten out of 10 observers reached the learning criterion with the middle gray background while only 10 out of 15 were able to reach the criterion with the black background. In addition, those observers who reached criterion on the black background still made significantly more errors than the observers presented with the middle gray background. There were no significant differences, however, in time to recall between the two types of backgrounds for observers who reached the learning criterion. These results are discussed in light of ΔE^*, a mathematical measure of perceived color differences.

Much of the current literature concerning performance on colored self-luminous displays has centered around how to make the colors more discriminable from one another. It is generally agreed that increasing color discriminability will also increase performance on many types of displays that incorporate color. Past research indicates that background luminance can affect color discriminability through at least two mechanisims, perceived color saturation and luminance contrast. Color discriminability should increase as color saturation and luminance contrast increase. Hunt (4), Burnham, Evans & Newhall (5) and Pitt & Winter (6) have all found that as background luminance increases, the perceived saturation of colors increases. It is also true, however, that low luminance (perceived black) backgrounds provide the greatest average luminance contrast with foreground colors. This creates a paradox for determination of ideal background luminance in relation to color discriminability. If luminance contrast is more important, then low luminance backgrounds should be used. If perceived saturation is more important, then higher luminance backgrounds should be used. This experiment will empirically test these opposing factors.

It is important to note that the studies which demonstrated an increase in perceived color saturation with higher luminance backgrounds were performed using colored papers and not self-luminous displays such as a Cathode Ray Tube (CRT) screen. The latter are qualitatively different from displays made up of surface colors, i.e., colored papers. The spectral distributions of surface colors tend to be very broad while the distributions for CRT colors tend to be narrow, especially for red phosphors. In addition, surface color differences are limited to luminance contrast ratios of no greater than approximately 30:1. This results from the fact that for normally colored papers, the best white reflects approximately 90% of the light falling on it while a very good black paper reflects only about 3% of the light falling on it, hence a luminance contrast ratio of 30:1. This is certainly not true of colors presented on CRT screens where the contrast ratios can be greater than 1000:1. Besides these differences between surface colors and CRT colors, another reason for investigating the effect of background or raster luminance is that little research has been done on relating the effect of raster luminance to actual performance measures for tasks presented on CRT screens.

In a previous study, Jacobsen (7) was able to demonstrate that as many as 20 colors presented on a CRT display can be accurately identified with only a minimal amount of practice by the observers. Each color was coded via a letter of the alphabet and observers had to learn which letter was paired with each color. On test trials, the colors were presented one at a time and observers were required to respond with the appropriate letter. The present study made use of the same paradigm in order to study the effect of raster luminance on the ability to code colors accurately. Two different raster luminances were used; one was perceptually black, the other appeared as a middle gray. These two specific luminances were used as the latter was used in the original color coding study and the former has been recommended by many as rendering the best color discriminability on CRT displays (8,9). In addition, the middle gray or intermediate luminance background was found by Pitt and Winters (6) to enhance color discrimination by increasing perceived saturation. The luminance of the middle gray background was chosen such that it was the median luminance of all of the 20 colored circles. Three different measures of color-coding ability were used: whether or not subjects could accurately encode all 20 colors, how many errors were made during learning and the time to recall the appropriate code during test presentations of the colors.

It has been suggested by Carter & Carter as well as others (10,11) that ΔE^*, which is based on the CIELUV color system, be used for measuring the perceived differences between colors presented on CRT displays. This measure takes into account both the difference in chromaticity, i.e., hue and saturation, as well as the difference in luminance between two samples. In some early research, Carter & Carter (11) report that measures of ΔE^* correlated well with performance on several visual tasks presented on CRT screens. There are, however, several problems with using this measure of color difference. One is that the equations for ΔE^* were derived for calculating small color differences and it is unclear whether the measure holds for very large color differences. A bigger problem may be the fact that ΔE^* does not take raster or background luminance into account. To the extent that background luminance affects color perception and ΔE^* is insensitive to backgound luminance differences, the validity of using ΔE^* as a measure of percieved color differences is questionable. In the previous study by Jacobsen, measures of ΔE^* did not correlate at all with performance measures on the color coding task such as the number of errors made during learning and time to recall color-coded information after learning had taken place. It was suggested that one of the reasons for this lack of correlation might have been the fact that the colored stimuli were presented on a luminous background instead of a completely dark raster. Consequently, the present study will again look at the relationship between ΔE^* and performance on the color-coding task. It is assumed that the correlation between the two will be higher when the colors are presented on the black raster than when they are presented on the middle gray raster.

METHOD

Subjects

Twenty-five men attending Submarine School at the Navy Submarine Base participated voluntarily. All were naive as to color-coding studies and had normal color vision as determined by the AO Pseudo-isochromatic Plates. Those who normally wore corrective lenses did so during the experiment. The observers were randomly assigned to the two raster luminance conditions, 10 in each. Twenty-five observers were run as five of the observers were unable to meet the learning criterion and were subsequently dropped from the study.

Apparatus

All presentations were viewed on an Advanced Electronics Design Color Graphics Terminal, Model 512 that was driven by a Digital PDP 11/04 computer. Observers were seated 50 cm. in front of the terminal screen. A fluorescent light above and behind the observer, shaded with neutral density filters, cast 4.5 fc of illumination on the CRT screen. The stimuli, twenty circles 2.0 cm (2.3 degrees of visual angle) in diameter, were presented in a four by five matrix and were separated by 2.0 cm (2.3 degrees of visual angle) vertically and 1.0 cm (1.15 degrees of visual angle) horizontally. Two digit numbers could be superimposed on each colored circle. The CIE (1931) coordinates of the twenty colors and the two raster backgrounds are given in Table 1. These coordinates were obtained with a Pritchard Model 1980 3-Filter photometer in the following manner. Each colored circle was visually matched to a Munsell sample that was illuminated by Illuminant C. The sample luminance was then measured with the three colored filters of the photometer. These measures, along with the actual CIE coordinates of the Munsell samples, were used to arrive at correction factors for the three filters of the photometer. The three filters were then used to measure the luminances of the colored circles and the correction factors were used to arrive at the CIE coordinates.

A microphone wired to a voice operated relay was connected to the computer in order to determine the subjects time to respond which was measured via an internal clock in the computer. The clock was started when a test circle appeared on the screen and the observer's verbal response triggered the voice actuated relay which stopped the clock.

Procedure

The task consisted of a study-test paired associates paradigm using set sizes of 2 to 20 colors. In the study phase, two digit numbers were paired with the colored circles by superimposing the numbers on circles. Observers were allowed to study the entire display for as long as they wished.

During the test phase, one colored circle at a time was randomly chosen by the computer and presented in the middle of the CRT screen. The observer's task was to respond verbally with the appropriate number. The response time and the actual response were both recorded. After all of the colors in the learning set had been presented once, the study phase was reinitiated using the same set of color-number pairs. The observer again controlled the length of time of this phase. A second test phase was then begun with a different random order of color stimuli presentations. This procedure of study-test was continued until the learning criterion of all correct responses in three consecutive test phases was met. The observer was then given an optional rest period after which a new learning set was introduced and the entire procedure was repeated.

Each learning set consisted of 2 to 20 color-number pairs. The set of 2 was always presented first followed by the set of 3, 4, etc. up to 20. Each subsequent set consisted of the previous color-number pairs plus one additional pair. However,the color sets were different for each observer. Consequently, only in the set size of 20 were the colors identical for all observers. Since the presentation of the numbers followed the same numerical order (11,12,13,14,etc.) for all observers, this counterbalancing of color sets ensured that the effect of set size was not confounded with whether some colors were more or less discriminable than other colors. Most observers took one or two rest periods during the session.

RESULTS

Color Identification

All 10 observers presented with the middle gray background were able to meet the learning criterion. However, 15 observers were presented with the black background because 5 were unable to meet the learning criterion and were not included in subsequent analyses. This left an even number of subjects in each background condition.

Color Mistakes as a Function of Set Size

The mean number of errors made by all observers for each set size during the learning phases is shown in Figure 1. A two-way split-plot (set size X background) ANOVA revealed a significant interaction effect between background and set size ($F(18,324)=1.8$; $p<.05$). Simple main effects tests

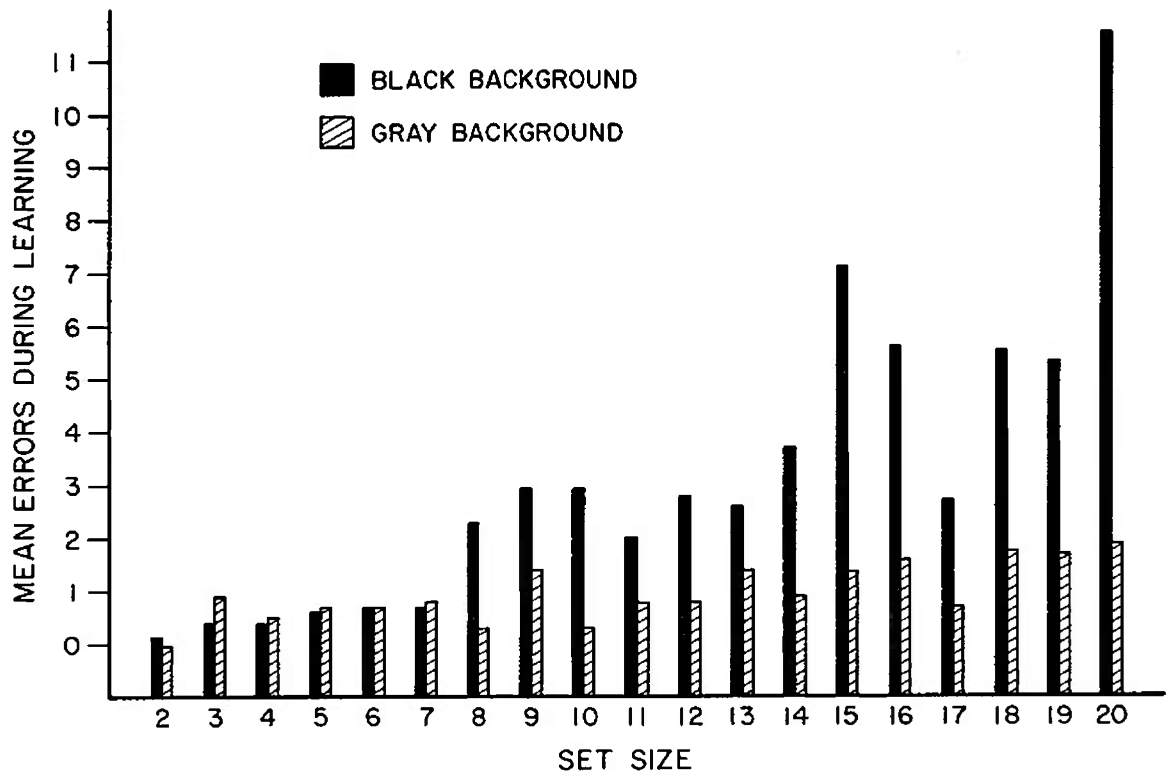

Figure 1. Mean number of color errors made during learning as a function of set size

showed that there were significantly more errors on the black background than on the middle gray background for set sizes of 15, 16, and 20. They also revealed significant differences among the different set sizes on the black background ($F(18,324)=4.81$; $p<.01$). The same was not true for colors presented on the middle gray background. Newman-Keuls means tests were performed on the set size differences for colors presented on the black background. These revealed that significantly more errors were made for the set of twenty than for any other set size. In addition, significantly more errors were made for the set size of 15 than for the set sizes of 2 through 7.

Color Mistakes as a Function of Color

The mean number of errors made for each color during learning by observers who met the learning criterion are shown in Figure 2. More errors were made for every color when presented on the black background than when they were presented on the middle gray background. A two-way split-plot ANOVA (color X background) revealed a significant interaction between color and background on the number of errors made during learning ($F(19,342)=2.78$; $p<.01$). A test of simple main effects revealed that light blue, red, dark green, olive, dark aqua, and slate yielded significantly more errors during learning when they were presented on the black than on the middle gray background. This test also revealed that there were significant differences between the number of errors made for colors presented on the black background ($F(19,342)=6.83$; $p<.01$). This was not true for colors presented on the middle gray background. Newman-Keuls means tests for the colors presented on the black background are summarized in Table 2. Basically the worst colors, in terms of errors made during learning, were dark aqua, olive, slate, and light blue.

Recall Time as a Function of Set Size

The effect of set size on time to recall was analyzed by obtaining an average time for each set size for each observer that met the learning criterion. This was achieved by computing the mean reaction time for responses that occurred in the last test phase for each set size. This test phase consisted of the last N responses for each set where N equals set size. By definition, these responses were all correct. These data were then averaged across observers and are presented in Figure 3. A two-way split-plot ANOVA (set size X background) revealed a significant main effect of set size ($F(18,324)=33.6$, $p < .01$). There was no significant interaction or main effect of background on time to recall. The two background conditions are displayed separately in Figure 3 even though no significant difference was found between the two, in order to show how close the performance was for the two

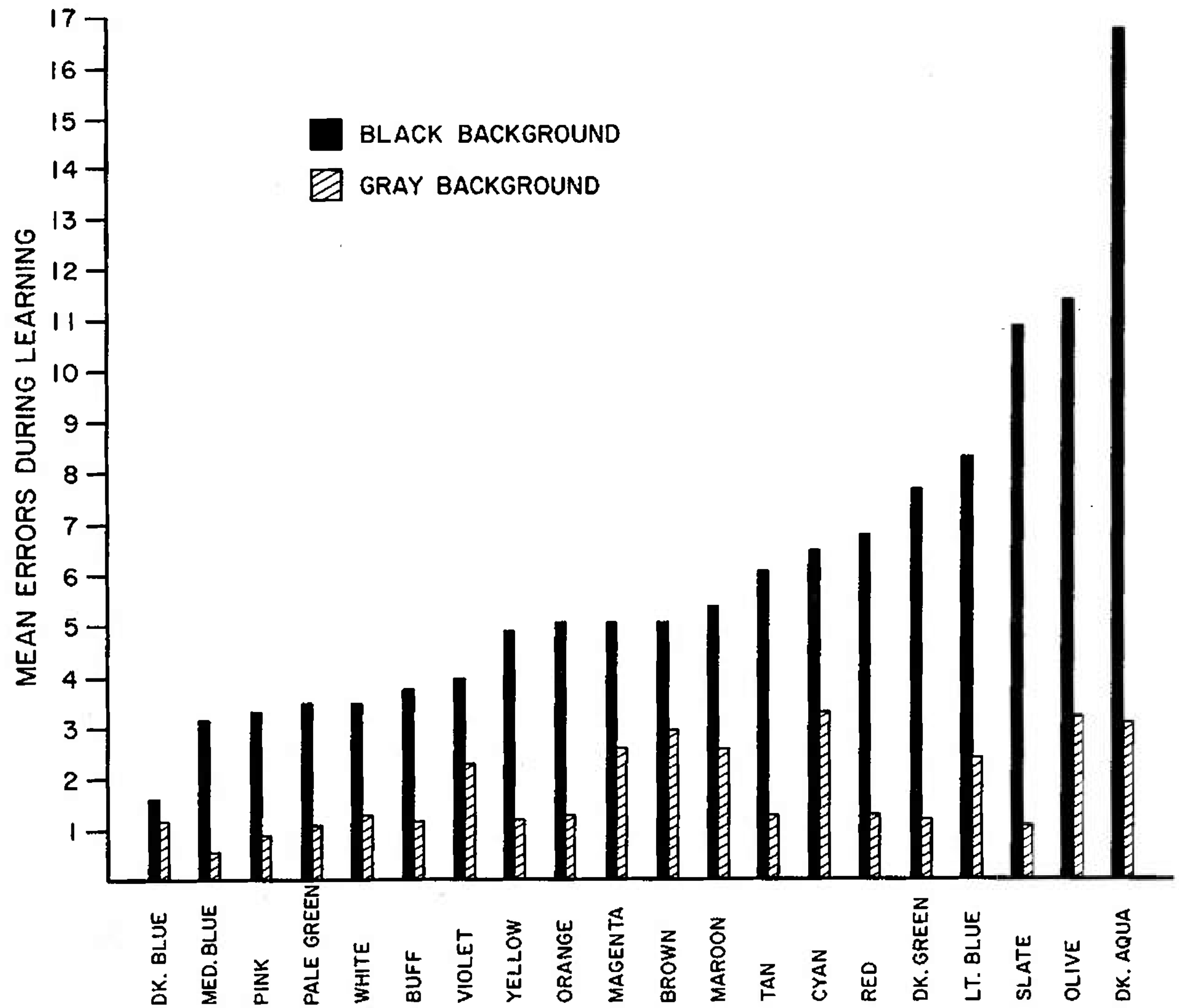

Figure 2. Mean number of color errors made during learning as a function of color.

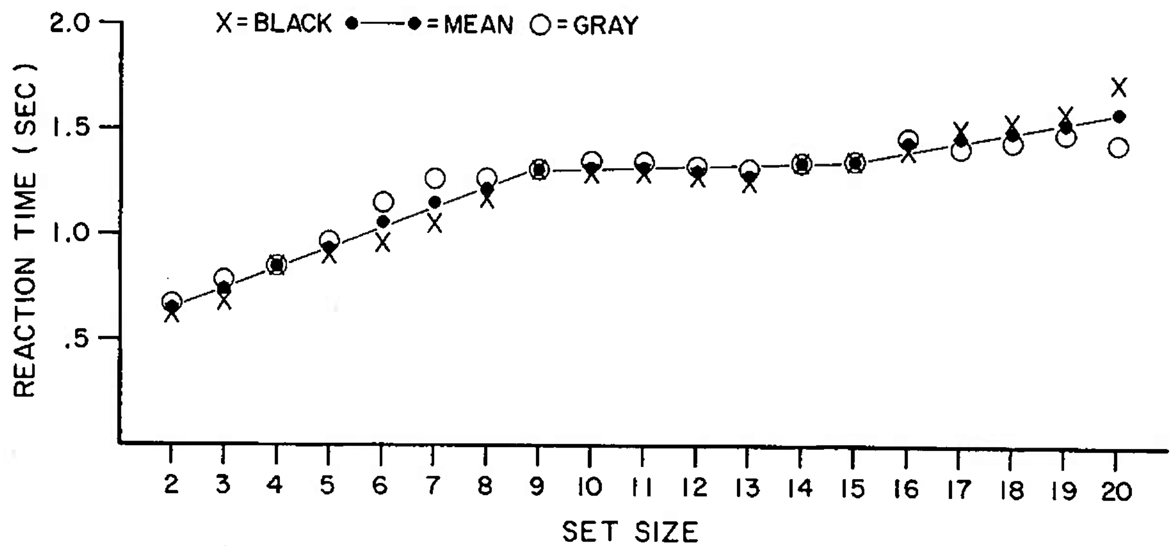

Figure 3. Time to recall color coded information as a function of set size.

backgrounds. Newman-Keuls means tests are summarized in Table 3. In general, it appears that time to recall increases fairly linearly with increases in set sizes from two through about eight or nine. No further significant rise in time to recall is observed for set sizes of 9 through 20. This flattening out of recall time with set sizes greater than 8 or 9 is identical to the results obtained in Jacobsen's (7) original study of the effect of set size on time to recall color-coded information.

Recall Time as a Function of Color

The reaction times recorded during the last test phase in the set size of 20 presentation were used to analyze the effect of color on reaction time. All colors were supposedly well-learned by this time and were identical for all observers. The mean time to recall each color presented on the black background versus the middle gray background can be seen in Figure 4. A two-way split-plot (color X background) ANOVA determined that there were significant differences between the recall times of the twenty colors ($F(19, 342)=4.79$, $p<.01$). The effect of background was not significant as a main effect or as an interaction effect. It is noteworthy, however, that in 15 of the 20 colors, the time to recall was higher for colors presented on the black background than for colors presented on the middle gray background. From Figure 4, one can see that this difference in recall times was as large as a factor of two or three for colors like slate, light blue, buff, and red. Unfortunately, the overall variance in the data appears to have precluded the statistical significance of these differences. A summary of Newman-Keuls means tests performed on the recall times for the twenty colors can be seen in Table 4.

Errors, Time to Recall and ΔE^*

The Pearson product moment correlation between time to recall and errors was 0.62 on the middle gray background and 0.83 with the black background. Several correlations were also computed between measures of ΔE^* and recall time and errors. Three measures of ΔE^* were used, the average ΔE^*, the smallest E* and the average of the two smallest ΔE^* values. If ΔE^* is a good measure in predicting performance, one would assume that as it increases, both errors and time to recall should decrease, giving a negative correlation. Table 5 gives the obtained correlations. None was statistically significant. In general, ΔE^* was a slightly better predictor of performance when the colors were presented on the black background than when they were presented on the middle gray background. In neither case, however, do the correlations warrant concluding that ΔE^* is a very good predictor of performance on this task.

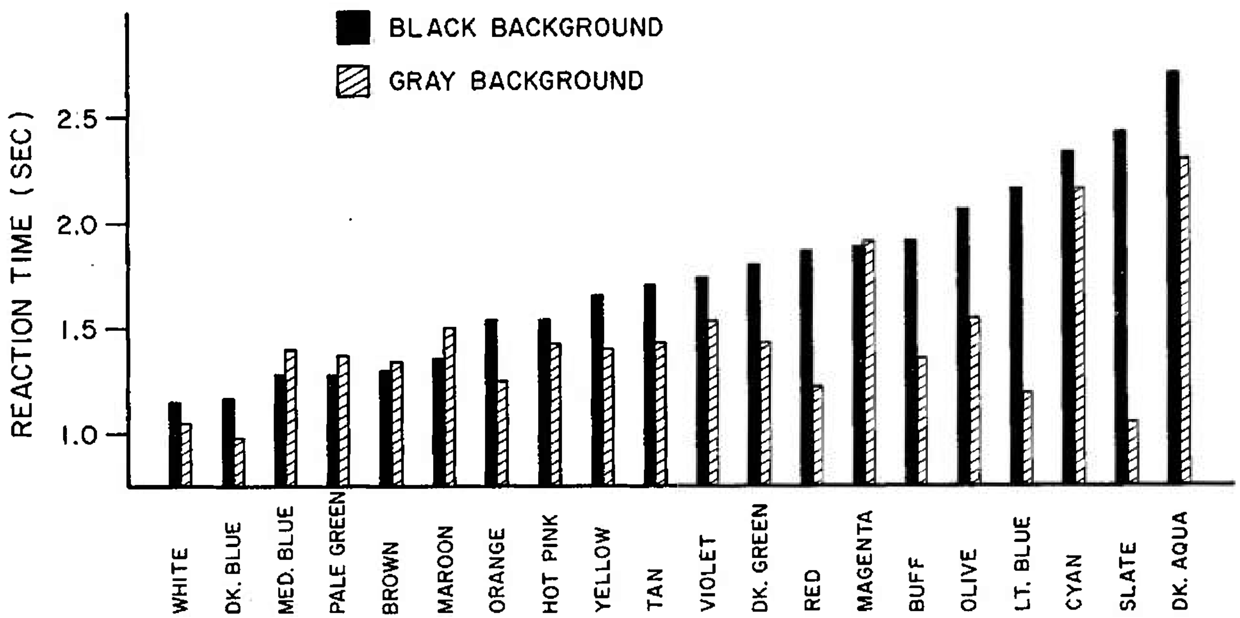

Figure 4. Time to recall color coded information as a function of color.

DISCUSSION

Several general conclusions can be drawn from this study. The first is that observers had much less difficulty with the intermediate luminance or middle gray background than with the low luminance or black background. This is evidenced by the fact that all 10 observers presented with the middle gray background were able to reach the learning criterion, while 5 out of 15 subjects presented with the black background were unable to reach the learning criterion even after more than four hours of practice. It should be noted that for observers presented with the middle gray background, none took longer than two hours to complete the entire study. In addition, even observers who met the learning criterion on the black background made significantly more errors during learning than obervers who were presented with the middle gray background. The former, consequently, had to have much more practice on the task than the latter. This difference in error rate and ability to reach the learning criterion may result from the fact that the colors were more discriminable on the middle gray background than on the black background.

A second major conclusion is that although observers had much more difficulty meeting the learning criterion on the black background, the time to recall the coded information did not differ significantly between the two backgrounds if the criterion was met. It therefore appears that a sufficient amount of practice enabled observers to overcome some of the difficulty in using the black background. Several studies have shown in the past that extended practice can enhance performance on discrimination tasks considerably (12,13). Hence, the present results are not without precedent.

A third general conclusion is that ΔE^* did not correlate well with performance on this task, although the correlation was slightly improved for stimuli presented on the black background. There are several explanations for this lack of correlation. One is that, as has already been expounded, learning can override many difficulties in discrimination. Hence, even though ΔE^* may correlate with perceived color differences, that does not ensure that it will correlate well with performance on well-practiced tasks. A second reason for the lack of correlation is that ΔE^* does not take background luminance into account. Hence, especially with the middle gray background, one would not expect ΔE^* to correlate well with performance or even perceived color differences. To a lesser extent this is also true for the colors presented on the black background since the background wasn't completely dark as it had a measured luminance of 0.09 fL that resulted from the ambient light being reflected off of the screen. We are currently investigating the effect of background on perceived chromatic and luminance differences in our laboratory in hopes of determining how background can be taken into account in the ΔE^* calculations.

One important note should be made here. The finding that color discrimination was better with the middle gray than with the black background might seem counter-intuitive since the contrast ratios of the colors should be higher with the black background. In one respect that is true; the average contrast ratio between the colors and the background is higher on the black background than on the middle gray background. However, this ignores one important effect of background luminance; it can create qualitative differences between colors. For example, if two colors have similar luminance values, a background luminance between the two will result in one color being darker than the background and the other being lighter. Even though the actual physical color difference between the two colors has not changed, this introduction of a qualitative difference will enhance the discriminability between the two. It is much easier to determine if a sample is lighter or darker than its background than to determine how much lighter or darker. This may explain why the middle gray background produced better color discrimination than the black background. The former was set at a level such that it was brighter than half of the twenty colors and darker than the other half. This then may have accentuated the perceived differences between the colors.

One caveat regarding the apparent increased discriminability of colors with a middle luminance background is that this effect may not hold for targets with small visual angles such as alpha-numeric characters. Santucci, Menu & Valot (14) have found that the most important factor in character visibility is luminance contrast and not hue or saturation. Consequently, the best raster luminance level to use is very much dependent on the type of display and task involved.

Since raster luminance appears to be an important factor in perceived color differences and hence task performance, it need be taken into account when colored displays are designed. A dark or low luminance raster is not always the best at achieving maximal discrimination between colors even though the average contrast ratio may be the highest on a dark raster. Future research should address itself to modifying the color difference equations so that raster luminance is taken into account.

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Table 1. CIE (1931) chromaticity coordinates for the twenty colors and two raster backgrounds. Luminance values are given in fL.

Color	Y	x	y
Light Blue	14.84	.18	.16
Yellow	44.53	.42	.46
Red	3.14	.51	.29
Pale Green	56.10	.27	.51
Violet	1.21	.27	.15
Orange	18.45	.55	.37
Dark Green	1.33	.29	.54
Magenta	19.91	.20	.09
Medium Blue	1.38	.16	.09
Olive	1.63	.38	.49
Brown	1.00	.37	.42
Buff	30.17	.37	.28
Cyan	22.31	.22	.33
Maroon	0.88	.50	.32
Tan	8.08	.39	.37
Hot Pink	15.92	.42	.19
Dark Aqua	3.11	.20	.27
Slate	1.93	.23	.21
White	84.50	.23	.25
Dark Blue	0.25	.18	.12
Gray Raster	5.89	.27	.28
Black Raster	0.09	.38	.40

Table 2. Summary of Newman-Keuls means tests on significant differences among mean errors during learning as a function of color presented on the black background. Only the significantly different times are given ($p < .05$). Colors are listed in order of least to most errors from top to bottom and from left to right. The numbers in the table represent the difference in response time, in seconds, between the various colors.

	Light Blue	Slate	Olive	Dark Aqua
Dark Blue	6.7	9.3	9.8	15.1
Medium Blue		7.8	8.3	13.6
Hot Pink		7.6	8.1	13.4
Pale Green		7.4	7.9	13.2
White		7.4	7.9	13.2
Buff		7.1	7.6	12.9
Violet		6.9	7.4	12.7
Yellow			6.5	11.8
Orange			6.3	11.6
Magenta			6.3	11.6
Brown			6.3	11.6
Maroon			6.0	11.3
Tan				10.6
Cyan				10.2
Red				9.9
Dark Green				9.0
Light Blue				8.4
Slate				5.8
Olive				5.3

Table 3. Summary of Newman-Keuls means tests on significant differences among recall times as a function of set size. Only significant differences between the means are printed ($p < .05$). Set sizes are listed in order of fastest to slowest recall time from top to bottom and from left to right. The numbers in the table represent the difference in response time, in seconds, between the various set sizes.

	4	5	6	7	8	13	9	12	10	11	16	14	15	17	18	19	20
2	.22	.30	.42	.51	.58	.64	.65	.67	.68	.68	.70	.71	.80	.82	.85	.88	.94
3	.13	.21	.33	.42	.49	.55	.56	.58	.59	.59	.61	.62	.71	.73	.76	.79	.85
4			.20	.29	.36	.42	.43	.45	.46	.46	.48	.49	.58	.60	.63	.66	.72
5				.21	.28	.34	.35	.37	.38	.38	.40	.41	.50	.52	.55	.58	.64
6					.16	.22	.23	.25	.26	.26	.28	.29	.38	.40	.43	.46	.52
7						.13	.14	.16	.17	.17	.19	.20	.29	.31	.34	.37	.43
8													.22	.24	.27	.30	.36
13															.21	.24	.30
9															.20	.23	.29
12																.21	.27
10																	.26
11																	.26
16																	.24
14																	.23

Table 4. Summary of Newman-Keuls means tests on significant differences among recall times as a function of color. Only significantly different means are given ($p < .05$). Colors are listed in order of fastest to slowest recall time from top to bottom and from left to right. The numbers in the table represent the difference in response time, in seconds, between the various colors.

	Olive	Magenta	Cyan	Dark Aqua
Dark Blue	.73	.82	1.16	1.42
White		.78	1.13	1.39
Brown			.92	1.18
Pale Green			.91	1.17
Medium Blue			.90	1.16
Orange			.85	1.11
Maroon			.81	1.06
Hot Pink			.76	1.02
Yellow			.71	.97
Red			.70	.96
Tan			.68	.93
Dark Green				.89
Violet				.87
Buff				.86
Light Blue				.83
Slate				.76
Olive				.69
Magenta				.60

Table 5. Correlation coefficients between various measures of ΔE^*, recall time and errors during learning.

	Mean ΔE^*	Mean of Two Smallest ΔE^*	Smallest ΔE^*
Black Background			
Recall Time	-.20	-.15	-.15
Errors	-.34	-.36	-.36
Gray Background			
Recall time	-.17	.08	.18
Errors	-.18	-.21	-.24

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color-coding; luminance contrast; color discrimination

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effect of background raster luminance on the ability to learn and recall color coded information was studied via a paired-associates paradigm. Twenty color circles, paired with two-digit numbers were presented on a color graphics CRT terminal. On test trials each colored circle was presented by itself and observers were required to verbally recall the two-digit number that was previously paired with the target color. Time to recall as well as actual responses were both recorded. Two raster luminance levels were tested; dark

20. continued

or perceptual black and one that appeared to be a shade of middle gray.

Ten out of 10 observers reached the learning criterion with the middle gray background while only 10 out of 15 were able to reach the criterion with the black background. In addition, those observers who reached criterion on the black background still made significantly more errors than the observers presented with the middle gray background. There were no significant differences, however, in time to recall between the two types of backgrounds for observers who reached the learning criterion. These results are discussed in light of ΔE^*, a mathematical measure of perceived color differences.